Upper Ocean Dynamics and Horizontal Variability in Low Winds

Robert A. Weller
Clark 204a MS 29, Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone: (508) 289-2508 fax: (508) 457-2163 email: rweller@whoi.edu
Grant Number: N00014-05-10090

LONG-TERM GOALS

Our long-range scientific objective is to observe and understand the temporal and spatial variability of the upper ocean, to identify the processes that determine that variability, and to examine its predictability. Air-sea interaction is of particular interest, but attention is also paid to the coupling of the sub-thermocline ocean to the mixed layer and to both the open-ocean and littoral regimes. We seek to do this over a wide range of environmental conditions with the intent of improving our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

OBJECTIVES

Little work has been done to explore air-sea interaction and upper ocean dynamics in very light winds, and few observations are available that describe the mesoscale and smaller scale horizontal variability of the upper ocean in such conditions. The objectives of this work are to observe and understand in low wind conditions: (1) how and why the vertical structure and properties of the surface boundary layer of the ocean (roughly the upper 20 to 50 m) evolve in time, and (2) how and why this evolution varies at horizontal lags of 10s of meters to 10s of kilometers on time scales of minutes to months. To do so we seek to observe and identify: (1) the processes that spatially modulate the vertical structure of the upper ocean (including the depth, salinity, temperature, and velocity of the mixed layer), (2) the processes at work at the base of the mixed layer (such as entrainment), and (3) the air-sea exchanges (fluxes of heat, freshwater, and momentum) that couple the boundary layers on horizontal scales of tens of meters up to 100 km.

APPROACH

The CBLAST-LOW (Coupled Boundary Layers Air-Sea Transfers – Low wind) collaborative research program was set up to address the need to better understand and predict the coupled boundary layers in low wind conditions. It combined observations (in situ and remotely sensed) at a site south of Martha's Vineyard, modeling, and simulations. Observational campaigns were carried out in the summers of 2001, 2002, and 2003. The site was selected because winds are often from offshore (from the south to southwest) with very large fetch while at the same time the synoptic variability yields a wide range of summer heating conditions. The air-sea interaction tower (ASIT) of the Martha's Vineyard Coastal Observatory (MVCO) is situated there approximately 4 km south of the island in 19 m of water. The major cooperative field effort, the Intensive Operating Period or IOP, was completed in August 2003. We participated in the field campaigns and then worked collaboratively on analysis of the observations.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
07/19/2010	FINAL	11/01/2004-09/30/2011

4. TITLE AND SUBTITLE
Upper Ocean Dynamics and Horizontal Variability in Low Winds

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-05-10090

5c. PROGRAM ELEMENT NUMBER
09PR07853-00

6. AUTHOR(S)
Robert A. Weller

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
Grants and Contracts Services
183 Oyster Pond Road, Fenno MS #39
Woods Hole, MA 02543-1531

8. PERFORMING ORGANIZATION REPORT NUMBER
11443

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Ronald J. Ferek
Office of Naval Research
875 North Rondolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited, Unclassified

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objectives of this work are to observe and understand in low wind conditions: (1) how and why the vertical structure and properties of the surface boundary layer of the ocean (roughly the upper 20 to 50 m) evolve in time, and (2) how and why this evolution varies at horizontal lags of 10s of meters to 10s of kilometers on time scales of minutes to months.

15. SUBJECT TERMS
Upper Ocean Dynamics, Horizontal Variability, Low Winds, Air-sea Interaction, sub-thermocline ocean

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert A. Weller
					19b. TELEPHONE NUMBER *(Include area code)* 508-289-2508

TASKS COMPLETED

In 2001 we tested methods to observe the vertical structure of temperature, T(z), of salinity, S(Z), of horizontal velocity, U(z), with high temporal resolutions and vertical resolutions down to 0.5 m at a number of points separated by several m to 10's of km, observed the surface forcing and examined how it varies horizontally in the CBLAST-LOW domain, and obtained CTD profiles and sections to aid in initialization of regional ocean models (Pritchard *et al.*, 2002). Surface moorings were deployed at the 40 km and 20 km upwind sites (Fig 1a) and left in until mid-August, collecting month-long records of the surface forcing and temporal evolution of the vertical structure of the ocean. For a week, we set and instrumented a 3-D array; twenty vertical strings of instruments were attached to the 3-D array with instruments from the surface down to 25 m, and a Doppler profiler was hung from the center of the net. We also deployed a long-line 2-D array 1 km in length perpendicular to the shoreline. After 3 days we recovered the long-line array. After 5 days we recovered the 3-D array. During that week, 135 CTD profiles were collected, including two sections from the tower site to 40 km offshore and one section parallel to the shore. Shipboard sampling was coordinated with flights of the LongEZ aircraft, instrumented by C. Zappa (LDEO) and A. Jessup (UW) for infrared imaging of SST (Zappa and Jessup, 2005). The 6 bottom-mounted temperature, pressure, salinity instruments with recovered in mid-August with the surface moorings. CTD and moored observations were provided to Wilkin to support his regional ocean model development.

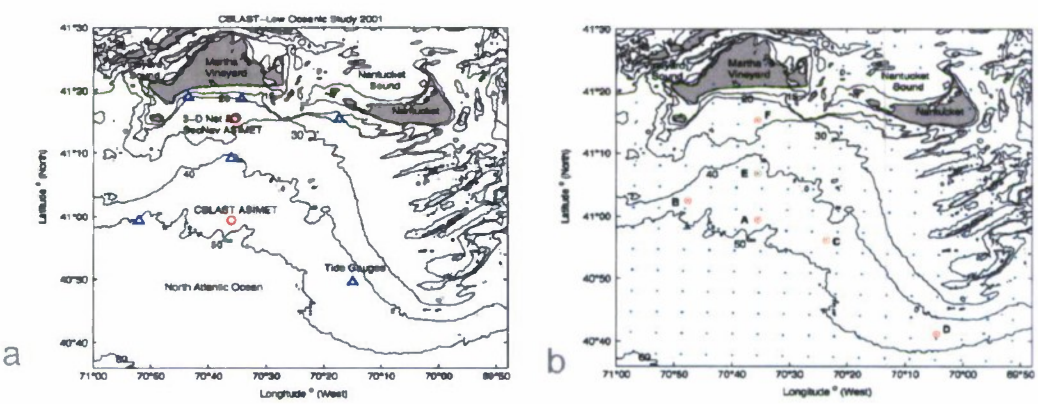

Figure 1. a) Locations of where the 3-D array, the two surface moorings (SecNav ASIMET and CBLAST ASIMET), and the six tide gauges (blue triangles) were deployed in 2001. b) Locations of the six surface moorings (A, B, C, D, E, F) deployed in 2002.

Apparent from the work in the summer of 2001 were the important roles of synoptic weather systems and regional oceanographic variability in setting the regional spatial context and of the energetic tidal currents and thermocline displacements that varied significantly both across and along isobaths in the region south of Martha's Vineyard. To better understand and document this variability and to concurrently examine the ability of regional atmospheric and ocean models to simulate this variability (and thus provide great support for the analysis of the observations), we deployed a six-mooring regional array (Fig. 1b) from late June to early September 2002. Data return from these moorings was high, and data have been made available to the modelers.

During the August 2003 Intensive Operating Period (IOP) surface meteorological and upper ocean measurements were collected from five heavily instrumented moorings, ten "light moorings", five drifting buoys with precision, fast-response thermistor chains, and the *F/V Nobska*. *F/V Nobska* was

instrumented to provide both direct and bulk flux estimates and also with a towed chain with fast-response temperature or temperature/salinity sensors at 0.5 m vertical spacing. The *F/V Nobska* was also equipped with upward- and downward-looking infrared radiometers to accurately measure the ocean skin temperature, and shipboard operations were coordinated with those of the aircraft collecting infrared imagery and atmospheric turbulence measurements. The mooring locations are shown in Figure 2a; Figure 2b shows representative drifter and tow tracks.

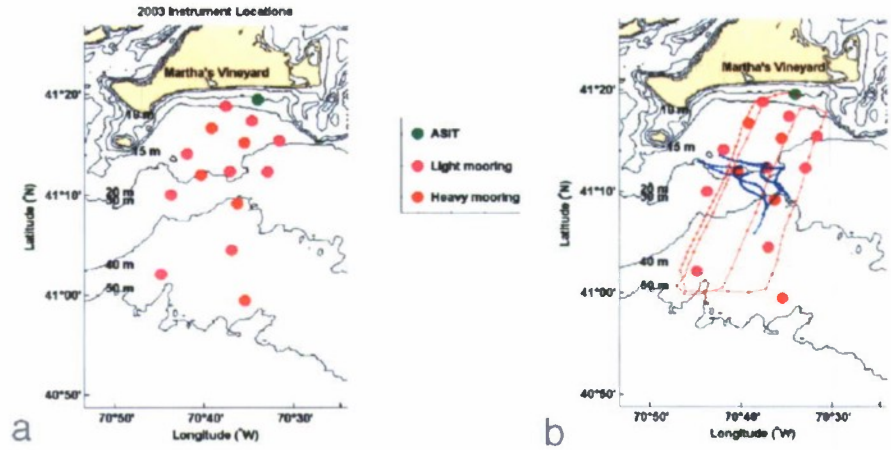

Figure 2. a) The locations of the 5 heavy surface moorings, 10 light moorings deployed in 2003 along with the location of the Air-Sea Interaction. b) Example tracks (blue) from one deployment of the drifting thermistor strings deployed during the IOP and of one deployment of the towed chain by FV Nobska (red) during the IOP to illustrate the additional sampling done over a wide range of spatial scales.

Data quality and return met or exceeded expectations during each phase of the field program. Technical reports have been written for the 2001 pilot experiment (Pritchard *et al.,* 2002), for the 2002 mooring deployments (Hutto *et al.,* 2003), and for the 2003 fieldwork (Hutto *et al*., 2005). Results based on analyses of our data have been presented at the 2004 AGU Ocean Sciences Meeting (Weller *et al.,* 2004; Farrar *et al.,* 2004a; Pritchard and Weller, 2004), the 2004 AMS Boundary Layers and Turbulence Conference (Farrar *et al.,* 2004b; Wang *et al.,* 2004), the 2004 International Geoscience and Remote Sensing Symposium (Thompson *et al.,* 2004), the 2006 AMS Conference on Hurricanes and Tropical Meteorology (Farrar *et al*., 2006; Zappa *et al*., 2006), and the 2006 AGU Fall Meeting (Weller *et al.*, 2006).

Initial data processing and quality control was completed (Pritchard *et al*., 2002; Hutto *et al*., 2003; Hutto *et al*., 2005). Meteorological data from the surface buoys deployed during the 2003 IOP have been made available to the public (http://uop.whoi.edu/completedprojects/cblast/data.html), and a gridded version of the subsurface mooring and shipboard data has been produced to facilitate use by collaborators and others.

Work then focused on analysis and publication of results (e.g., Pritchard and Weller, 2005; Edson *et al*., 2007; Farrar *et al*., 2007; Wells *et al., 2009*).

RESULTS

We have had three foci in recent work: (1) improved understanding of the processes responsible for increased SST variability under low winds, (2) characterization of the evolution and variability of the coupled boundary layers in a range of conditions, and (3) assessments of the predictive skill of regional models of the ocean and atmosphere (ROMS and COAMPS) combined with collaborative work addressed at identifying and improving shortcomings in the models. Work in each of these areas of progress will be addressed briefly below.

Under low-wind conditions, quasi-periodic spatial variability in SST up to several tenths of a °C was observed in the aerial infrared imagery at a scales ranging from 100 m to kilometers (Figure 3). Similar variability has been observed previously under low-wind conditions and associated with oceanic internal waves (Walsh *et al.*, 1998; Marmorino *et al.*, 2004). However, coincident measurements of the subsurface thermal structure associated with these surface temperature features were lacking; and attribution of the surface signature to a specific mechanism was not conclusive. Walsh *et al.* (1998) hypothesized that the internal-wave SST signals resulted from modulation of vertical mixing at the base of the O(1 m)-thick warm layer that forms under conditions of low winds and strong insolation, whereas Marmorino *et al.* (2004) hypothesized that the SST signal is caused by internal-wave modulation of the cool-skin effect. (The cool skin is an O(1 mm)-thick layer of relatively cool water that exists because of sensible, latent, and longwave-radiative heat loss from the sea surface.)

These hypotheses for the existence of SST variability associated with internal-waves under low-wind conditions were tested using the coincident observations of skin temperature (measured radiometrically) and subsurface temperature (measured with a towed instrument chain) from the *F/V Nobska* during CBLAST-Low. If the cool-skin modulation hypothesis of Marmorino *et al.* (2004) was correct, then the internal-wave signal would be expected to exist only in the skin temperature (or at least be significantly different from the internal-wave signal measured in subsurface temperature at 10-20 cm depth). In contrast, if the warm-layer modulation hypothesis of Walsh *et al.* (1998) was correct, then the internal-wave signal in skin temperature would be expected to be essentially the same as the signal observed at 10-20 cm depth (within the warm layer). Our observations show unambiguously that the organized variability in skin temperature observed from the ship and aircraft is also present in the subsurface temperature, indicating that the cool-skin modulation hypothesis does not explain the internal-wave signal observed in the skin temperature (Figure 4). In addition, numerical experiments conducted using a 1-D upper-ocean model (Price *et al.*, 1986) that can accurately simulate the formation and evolution of a warm layer under low winds show that the warm-layer modulation hypothesis of Walsh *et al.* (1998) is a plausible mechanism for the observed surface temperature signal. The observations motivated a flow up study in the fluid dynamics lab to examine further the straining of the cool skin (Wells *et al.*, 2009).

One of the primary goals of shipboard sampling and the deployment of the moored array during the CBLAST-Low field program was to better understand horizontal variability of SST and of the oceanic boundary layer in low wind conditions. These results explain one mechanism for the observed increase in small scale variability in SST under low winds; oceanic internal waves can significantly perturb the shallow, warm layer that forms in such conditions.

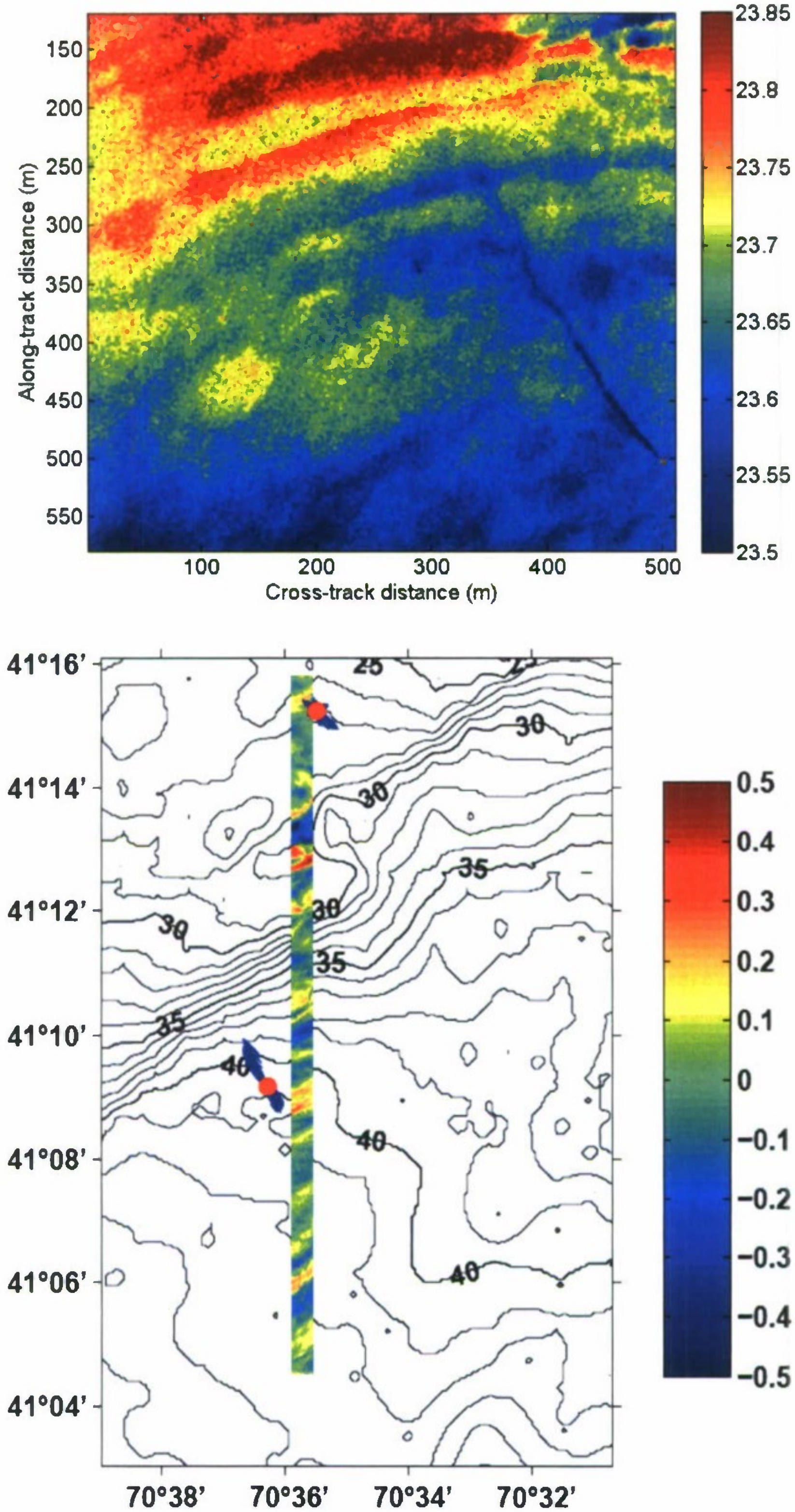

Figure 3. Upper panel: Raw sea surface temperature from aerial infrared imagery on 08-15-2003, a day of low winds (°C). Lower panel: Variability of infrared SST relative to 1.7 km along-track smoothed SST on the same day. The red dots indicate locations of air-sea interaction moorings and the blue vectors show internal-wave velocity signals observed at the moorings during the time of the aircraft overpass. Both panels are examples of the organized SST variability associated with oceanic internal gravity waves in low-wind conditions.

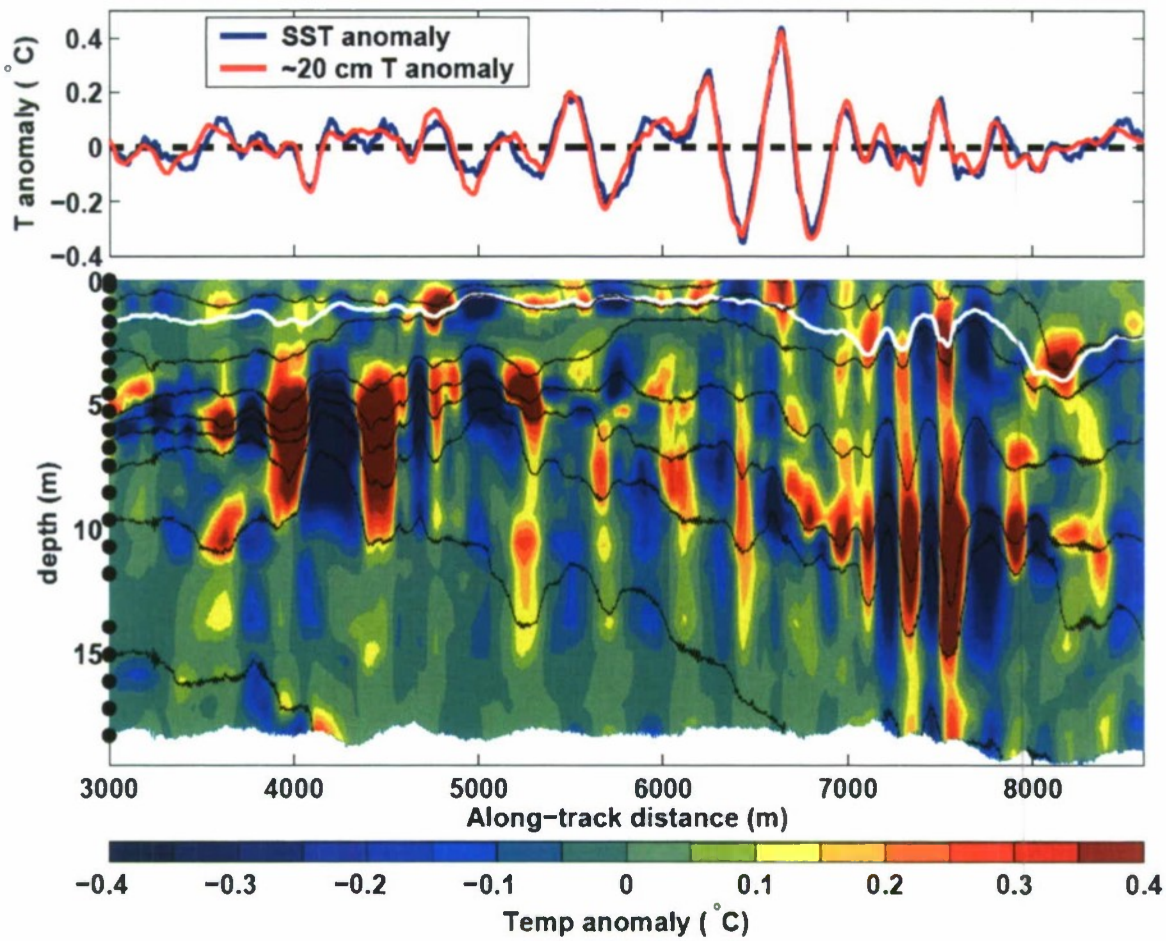

Figure 4. 90-500 m along-track band-passed temperature during the ship survey carried out on 08-15-2003 (the same day and region as the aircraft data shown in Figure 3). Upper panel: Signal in skin temperature and in the shallowest subsurface temperature measurement (mean depth of 20 cm during the interval shown). Lower panel: Signal in subsurface temperature. The black dots on the left side of the figure mark the nominal measurement depths. The black lines indicate (unfiltered) isotherm depths at 1°C intervals, and the heavy white line marks the depth where the subsurface temperature is 1°C less than the SST (to give a rough indication of the base of the "warm layer" referred to in the text). The fact that the two curves in the upper panel are essentially the same indicates that the skin temperature signal is not due to modulation of the cool-skin effect.

Over several days in 2001, the 3D moored array captured, for the first time, the 4D (space-time) evolution of temperature as well as vertical profiles of velocity during the passage of packets of nonlinear internal waves (Pritchard and Weller, 2007). The properties of these waves are similar to ones observed during the 2002 and 2003 CBLAST-Low fieldwork (Pritchard and Weller, 2005; Zappa and Jessup, 2005; Farrar *et al.*, 2006). Analysis of the 3D-array data shows significant tidal modulation of mixed-layer and bottom boundary layer depth, and a rough diagnosis of terms in water-column energy budget suggests that the internal waves may be responsible for a significant fraction of the energy dissipation on the shelf.

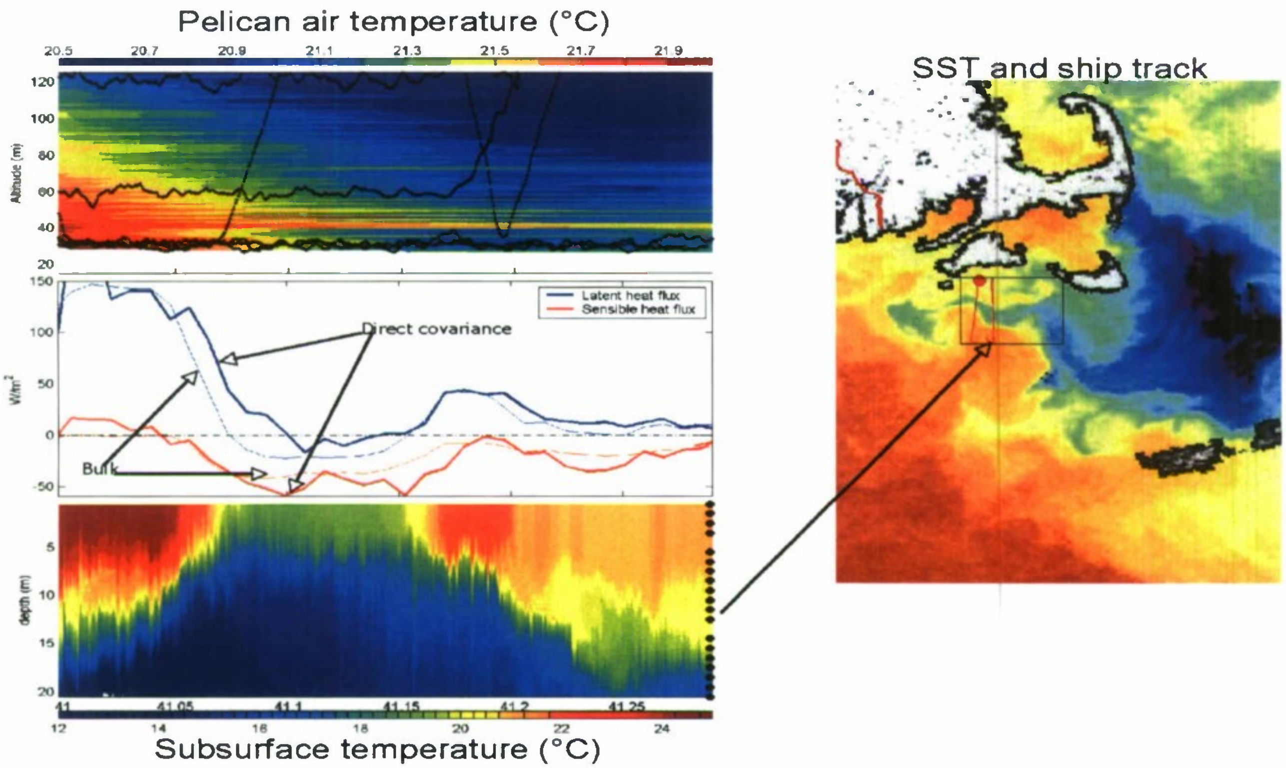

Figure 5. On the left, subsurface thermal structure (lower), sensible and latent surface heat fluxes (middle), and atmospheric temperature from the Pelican aircraft (upper) associated with the ship track shown on the right executed on the afternoon of August 19, 2003. (Figure from Edson et al., 2007; copyright, American Meteorological Society.)

Other analysis has allowed identification of some periods when the ocean responded strongly to atmospheric forcing, as well as periods when the atmosphere responded strongly to oceanic forcing. For example, Figure 5 shows that as the ship crossed SST variability associated with a cool intrusion from the east, there was spatial modulation of sensible and latent surface heat fluxes and of atmospheric temperature as observed by the Pelican aircraft. There is a very strong spatial modulation of the surface heat flux at the southern edge of the cold SST filament, with a combined change in latent and sensible heat flux of more than 150 W m^{-2} over a distance of about 5 km. The "cool filament" seen in SST in Figure 5 is a feature that recurs frequently and is visible in the June-August mean SST during 2002 and 2003. Working under the hypothesis that the cool feature is due to advection of cool water from the tidal mixing front found over Nantucket Shoals to the east (He and Wilkin, 2006), we are working to understand the origin and dynamics of this feature using the mooring, ship, and drifter data.

Our data from the three summers includes time series at fixed points of surface meteorology, air-sea fluxes, and ocean variability; it also includes CTD sections and swaths of high resolution ocean sampling from the drifters and the towed chain. We have been working with S. Wang (NRL) to examine the success of COAMPS at predicting the surface meteorological and air-sea flux fields. With good air-sea flux fields, ocean models can be run to examine their realism. We have been working with J. Wilkin (Rutgers) to evaluate ROMS model runs. Initial efforts focused on using the *in situ* oceanographic data from 2002 to evaluate ROMS model runs that are identical except for the vertical mixing parameterization employed (Wilkin and Lanerolle, 2004). The various mixing schemes lead to significantly different model simulations; of the three mixing schemes tested, the simulation using the KPP mixing scheme is the most realistic, particularly in simulation of SST and mean currents.

IMPACT FOR SCIENCE

The observations of the surface meteorological and air-sea flux fields and of the structure and variability of the littoral ocean are unique. They provide the basis for determination of processes at work in governing the variability of the shallow, coastal ocean and lower atmosphere. They also provide a basis for testing the realism of atmospheric, ocean, and coupled models of the coastal region and for improving coastal predictions by developing, testing, and implementing model improvements.

Our work with Zappa and Jessup to understand the contribution of oceanic internal gravity waves to horizontal variability of SST in low wind conditions (Farrar *et al.*, 2007) has potential applications for remote sensing. This new understanding of the signatures of internal waves in aerial infrared imagery will aid in interpretation of infrared imagery. Coherent variability at internal-wave scales (10's of m to km) seen in infrared imagery obtained in low-wind, daytime conditions should be interpreted as being likely due to internal waves. These findings are also of interest for understanding the potential contamination of large-scale satellite estimates of SST by unresolved internal wave signals.

RELATIONSHIPS TO OTHER PROGRAMS

This work is closely related to our studies of horizontal variability and predictability that were supported by a Secretary of the Navy/Chief of Naval Operations Chair. That work has focused on the impact of environmental variability on mine countermeasures activities in the shallow water. CBLAST-LOW, with its explicit sampling of the horizontal as well as vertical and temporal dimensions, has provided exceptional observations of the structure and variability of the littoral ocean. We worked closely with Chris Zappa (LDEO) and Andy Jessup (UW APL) on joint analyses of their aircraft observations of the ocean's surface together with our in-situ data. We are also worked with Djamal Khelif (U. Cal. Irvine) and James Edson (U. Conn.) on joint analyses of the ship and aircraft survey data.

USN Midshipwoman Tenley Fullington was hosted for an internship at WHOI to work with the data collected in CBLAST-LOW.

In 2007, a summer student fellow of the WHOI Geophysical Fluid Dynamics Program (Andrew Wells of Cambridge Univ.) undertook a laboratory study of the effect of hydrodynamic straining on the cool skin. This project was motivated by CBLAST-Low observations (e.g., Figure 3) and analysis (Farrar *et al.*, 2007). The objective was to determine whether modulation of the cool-skin effect by internal waves or other convergent or divergent surface flow patterns can produce a measurable effect in infrared observations of the sea surface as has been suggested (Osborne, 1965; Marmorino *et al.*, 2004;

Zappa *et al.*, 2005). The results of the theoretical and laboratory study show that the theoretical model of Osborne (1965) does a reasonably good job of predicting the surface temperature signal associated with a divergent surface flow, but the signal is likely to be small (10^{-3}-10^{-2} °C) for most geophysical flows, including internal waves. Results were published (Wells *et al.,* 2009).

REFERENCES

Edson, J., T. Crawford, J. Crescenti, T. Farrar, N. Frew, G. Gerbi, C. Helmis, T. Hristov, D. Khelif, A. Jessup, H. Jonsson, M. Li, L. Mahrt, W. McGillis, A. Plueddemann, L. Shen, E. Skyllingstad, T. Stanton, P. Sullivan, J. Sun, J. Trowbridge, D. Vickers, S. Wang, Q. Wang, R. Weller, J. Wilkin, D. Yu, and C. Zappa. The Coupled Boundary Layers and Air-Sea Transfer experiment in low winds (CBLAST-LOW). *Bulletin of the American Meteorological Society,* 88(3), 341-356.

Farrar, J.T., Weller, R.A., Zappa, C., and Jessup, A.T. 2004a. Subsurface expressions of sea surface temperature variability under low winds. *16th Symposium on Boundary Layers and Turbulence.* Ref. P8.1, American Meteorological Society, Portland, Maine, USA.

Farrar, J. T., R. Weller, and J. Edson. 2004b. Observations of the coupled air-sea boundary layers during the 2003 CBLAST-Low field program. *Eos Trans. AGU,* 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-02, 2004.

Farrar, J.T., Zappa, C., Weller, R.A., and Jessup, A.T. 2007. Sea surface temperature signatures of oceanic internal waves in low winds. *J. Geophysical Research., 112,* C06014, doi:10.1029/2006JC003947.

Hagan, D., D. Rogers, C. Friehe, R. Weller, and E. Walsh, 1997. Aircraft observations of sea surface temperature variability in the tropical Pacific, *Journal of Geophysical Research, 102,* 15733-15747.

Hutto, L., J. Lord, P. Bouchard, R. Weller, and M. Pritchard, 2003. SecNav/CBLAST 2002 Field Experiment: Deployment/Recovery Cruises and Data Report, F/V Nobska, June 19-20, 2002, F/V Nobska, September 4 and 9, 2002, Mooring Data, June 19-September 9, 2002, Upper Ocean Processes Group Technical Report, UOP 03-03, Woods Hole Oceanographic Institution, Woods Hole, Ma.

Hutto, L., T. Farrar, and R. Weller, 2005. CBLAST 2003 Field Work Report, Technical Report, WHOI 2005-04, Woods Hole Oceanographic Institution, Woods Hole, Ma.

Large, W. G., J. C. McWilliams, and S. C. Doney, 1994. Oceanic vertical mixing: a review and a model with nonlocal boundary layer parameterisation, *Rev. Geophys* , *32* , 363-403.

Marmorino, G.O., G.B. Smith, and G.J. Lindemann, 2004. Infrared imagery of ocean internal waves, *Geophys. Res. Lett.,* 31, L11309, doi:10.129/2004GL020152.

Osborne, M.F.M., 1965. The effect of convergent and divergent flow patterns on infrared and optical radiation from the sea, *Dt. Hydrogr. Zeitschrift* , 18, 1-25.

Price, J. F., R. A. Weller, and R. Pinkel, 1986. Diurnal cycling: observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing, *Journal of Geophysical Research, 91,* 8411-8427.

Pritchard, M., J. Gobat, W. M. Ostrom, J. Lord, P. Bouchard, and R. A. Weller, 2002. CBLAST-Low 2001 Pilot Study, Mooring Deployment Cruise and Data Report: FV Nobska, June 4 to August 17, 2002, Upper Ocean Process Group Technical Report, WHOI-2002-03, Woods Hole Oceanographic Institution, Woods Hole, Ma.

Pritchard, M. and R. A. Weller, 2002. Simultaneous measurements of spatial and temporal variability in the oceanic upper mixed layer. 2002 Ocean Sciences Meeting, Honolulu, Hawaii, 11-15 February 2002.

Pritchard, M. and R. A. Weller, 2004. High Frequency Varability on the New England Shelf during the 2001 CBLAST-Low Pilot Experiment. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-17.

Pritchard, M. and R.A. Weller, 2005. Observations of internal bores and waves of elevation on the New England inner continental shelf during summer 2001. *J. Geophys. Res.*, 110, C03020, doi:10.1029/2004JC002377.

Skyllingstad, E.D., Vickers, D., and Mahrt, L. 2004. Effects of spatial variability of SST on the marine boundary layer. 16th Symposium on Boundary Layers and Turbulence. Ref. 8.3, American Meteorological Society, Portland, Maine, USA.

Thompson, D. R., Monaldo, F. M., Elfouhaily, T. M., Farrar, J. T., Weller, R. A., and Grimmett, T. K., 2004. Comparison of High-Resolution Wind Maps from EnviSAT and RadarSAT SAR Imagery with In Situ Measurements from the CBLAST Experiments. *IEEE International Geoscience and Remote Sensing Symposium*, Anchorage, Sept 2004.

Walsh, E.J., R. Pinkel, D. E. Hagan, R. A. Weller, C. W. Fairall, D. P. Rogers, S. P. burns, and M. Baumgartner, 1998. Coupling of internal waves on the main thermocline to the diurnal surface layer and sea surface temperature during the Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment. *Journal of Geophysical Research, 103*, 12613-12628.

Wang, S., Q. Wang, Z. Gao, J. Edson, R. Weller, and C. Helmis, 2004. Evalutaion of COAMPS Real Time Forecast for CBLAST-LOW Summer Experiments 2002/2003. American Meteorological Society, Portland, Maine, USA.

Weller, R.A., Farrar, J.T., Hutto, L., Zappa, C and Thompson, D. R., 2004. Spatial and temporal scales of oceanic variability in the CBLAST-Low study region. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-03.

Wells, A. J., C. Cenedese, J. T. Farrar, and C. J. Zappa, 2009. Variations in ocean surface temperature due to near-surface flow: straining the cool skin layer. *Journal of Physical Oceanography*, 29, 2685-2710.

Wilkin, J. and Lanerolle, L., 2004. Modeling the Summertime Heat Budget of Southeast New England Shelf Waters. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-11.

Zappa, C. J. and A. T. Jessup, 2004. Variability of ocean skin temperature from airborne infrared imagery during CBLAST-Low. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-04, 2004.

Zappa, C. J. and A. T. Jessup, 2005. High-resolution airborne infrared measurements of ocean skin temperature. *Geoscience and Remote Sensing Letters, IEEE*, 2(2), 146-150.

PUBLICATIONS

Edson, J., T. Crawford, J. Crescenti, T. Farrar, N. Frew, G. Gerbi, C. Helmis, T. Hristov, D. Khelif, A. Jessup, H. Jonsson, M. Li, L. Mahrt, W. McGillis, A. Plueddemann, L. Shen, E. Skyllingstad, T. Stanton, P. Sullivan, J. Sun, J. Trowbridge, D. Vickers, S. Wang, Q. Wang, R. Weller, J. Wilkin, D. Yu, and C. Zappa. The Coupled Boundary Layers and Air-Sea Transfer experiment in low winds (CBLAST-LOW). *Bulletin of the American Meteorological Society,* 88(3), 341-356. [published, refereed]

Farrar, J.T., Weller, R.A., Zappa, C., and Jessup, A.T. 2004a. Subsurface expressions of sea surface temperature variability under low winds. *16th Symposium on Boundary Layers and Turbulence.* Ref. P8.1, American Meteorological Society, Portland, Maine, USA. [published]

Farrar, J.T., Weller, R.A., Zappa, C., and Jessup, A.T. 2006. Sea surface temperature signatures of oceanic internal waves in low winds. *27th Conference on Hurricanes and Tropical Meteorology.* Ref. P11.2, American Meteorological Society, Monterey, California, USA.

Farrar, J.T., Zappa, C., Weller, R.A., and Jessup, A.T. 2007. Sea surface temperature signatures of oceanic internal waves in low winds. *J. Geophysical Research., 112*, C06014, doi:10.1029/2006JC003947. [published, refereed]

Farrar, J. T., R. Weller, and J. Edson. 2004b. Observations of the coupled air-sea boundary layers during the 2003 CBLAST-Low field program. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-02, 2004. [published]

Hutto, L., J. Lord, P. Bouchard, R. Weller, and M. Pritchard, 2003. SecNav/CBLAST 2002 Field Experiment: Deployment/Recovery Cruises and Data Report, F/V Nobska, June 19-20, 2002, F/V Nobska, September 4 and 9, 2002, Mooring Data, June 19-September 9, 2002, Upper Ocean Processes Group Technical Report, UOP 03-03, Woods Hole Oceanographic Institution, Woods Hole, Ma. [published]

Hutto, L., T. Farrar, and R. Weller, 2005. CBLAST 2003 Field Work Report, Technical Report, WHOI 2005-04, Woods Hole Oceanographic Institution, Woods Hole, Ma. [published]

Pritchard, M., J. Gobat, W. M. Ostrom, J. Lord, P. Bouchard, and R. A. Weller, 2002. CBLAST-Low 2001 Pilot Study, Mooring Deployment Cruise and Data Report: FV Nobska, June 4 to August 17, 2002, Upper Ocean Process Group Technical Report, WHOI-2002-03, Woods Hole Oceanographic Institution, Woods Hole, Ma. [published]

Pritchard, M. and R. A. Weller, 2002. Simultaneous measurements of spatial and temporal variability in the oceanic upper mixed layer. 2002 Ocean Sciences Meeting, Honolulu, Hawaii, 11-15 February 2002. [published]

Pritchard, M. and R. A. Weller, 2004. High Frequency Varability on the New England Shelf during the 2001 CBLAST-Low Pilot Experiment. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-17. [published]

Pritchard, M. and R.A. Weller, 2005. Observations of internal bores and waves of elevation on the New England inner continental shelf during summer 2001. *J. Geophys. Res.*, 110, C03020, doi:10.1029/2004JC002377. [published, refereed]

Pritchard, M. and R.A. Weller, 2007. Space/time variability in shallow coastal waters: the contribution of shoaling internal waves. *J. Geophys. Res.* [submitted]

Thompson, D. R., Monaldo, F. M., Elfouhaily, T. M., Farrar, J. T., Weller, R. A., and Grimmett, T. K., 2004. Comparison of High-Resolution Wind Maps from EnviSAT and RadarSAT SAR Imagery with In Situ Measurements from the CBLAST Experiments. *IEEE International Geoscience and Remote Sensing Symposium*, Anchorage, Sept 2004. [published]

Weller, R.A., Farrar, J.T., Hutto, L., Zappa, C and Thompson, D. R., 2004. Spatial and temporal scales of oceanic variability in the CBLAST-Low study region. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-03. [published]

Zappa, C., and Jessup, A.T., Farrar, J.T., Weller, R.A., 2006. Coherent structures in ocean skin temperature variability. *27th Conference on Hurricanes and Tropical Meteorology*. Ref. 7C.8, American Meteorological Society, Monterey, California, USA. [published]